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**ON-ORBIT DEPLOYMENT ANAMOLIES:
WHAT CAN BE DONE?**

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ABSTRACT

Modern communications satellites rely heavily upon deployable appendage (i.e. solar arrays, communications antennas, etc.) to perform vital functions that enable the spacecraft to effectively conduct mission objectives. Communications and telemetry antennas provide the radio-frequency link between the spacecraft and the earth ground station, permitting data to be transmitted and received from the satellite. Solar arrays serve as the principle source of electrical energy to the satellite, and re-charge internal batteries during operation. However, since satellites cannot carry back-up systems, if a solar array fails to deploy, the mission is lost.

This article examines the subject of on-orbit anomalies related to the deployment of spacecraft appendage, and possible causes of such failures. Topics discussed shall include mechanical launch loading, on-orbit thermal and solar concerns, reliability of spacecraft pyrotechnics, and practical limitations of ground-based deployment testing. Of particular significance, the article will feature an in-depth look at the lessons learned from the successful recovery of the Telesat Canada Anik-E2 satellite in 1991.

INTRODUCTION

Although spacecraft failures occur in many different ways, the majority of satellite anomalies in recent years have occurred during the early launch stages. Launch vehicles have exploded several seconds after liftoff; others have been destroyed remotely after going awry by safety engineers; and still some have never even left the launch pad. The unfortunate consequence of this destructive process is that the payload, usually one or more multi-million dollar communication satellites, is also lost.

In a similar respect, the spacecraft that have managed to safely make it into orbit amide the severity of vehicle launch, have themselves found unique ways to fail. The Japanese Superbird A satellite became useless in space after expelling critical oxidizing propellant in late December 1990, resulting in a \$170 million insurance claim by owner Space Communications Corporation, Tokyo (ref. 1); electrical problems crippled the European Space Agency's (ESA) Olympus satellite in 1991 for two months, before ground engineers were able to regain control of the spacecraft (ref. 2); and propulsion problems caused the ESA Hipparcos satellite to be placed in the wrong orbit in 1989, forcing officials to resort to a "revised mission" in order for the spacecraft to achieve its objectives (ref. 3).

However, the most puzzling and subsequently the most unpredictable flight anomalies have generally involved malfunctions related to spacecraft appendage deployment (i.e. solar arrays, communication antennas, booms, etc.). Table 1 shows a partial list of spacecraft failures of late

(1980-present) which were attributed to their inability to deploy appendage on orbit. The table is based upon a previous database compiled by Thomas W. Trafton of the Aerospace Corporation (ref. 4). Of significance, the West German TVSat 1 satellite failed to deploy one of its two outer, four-segment solar array panels after orbital insertion by an Ariane 2 vehicle on November 20, 1987. This catastrophic event, which also prevented the satellite's receive antenna from being deployed, eventually forced the spacecraft's owners, the Eurosatellite European consortium, to abandon the satellite in space several months later. The satellite, valued at \$230 million, was eventually claimed as a \$51 million in-orbit insurance loss (ref. 5).

In April 1991, two well-publicized spacecraft deployment problems occurred which involved the Telesat Canada Anik-E2 satellite and the NASA Galileo Jupiter spacecraft. The Anik-E2 experienced difficulties deploying both of its K-band and C-band antennas, while ground controllers at the Jet Propulsion Laboratory (JPL) were unable to properly unfurl the high gain antenna of the Galileo spacecraft. Circumstances and events surrounding these failures have been well documented in public literature, and it would be redundant to re-examine them here. Also, the author feels that individuals within these two organizations are the best sources for such detailed information and mission status. However, several important lessons learned from the successful Anik-E2 recovery shall be discussed in a later section of this paper.

There have also been several less announced instances of spacecraft experiencing problems deploying appendage, most of these payloads were launched from the U.S. Space Transportation System (STS) or Space Shuttle. Due to the advent of the Space Shuttle in the early 1980s, numerous on-orbit catastrophes have been auspiciously avoided. Various satellites failed to deploy solar arrays, antennas, etc., when commanded, despite futile maneuvers by ground controllers. The Shuttle's Remote Manipulator Arm or "Canadarm", designed and built by Spar Aerospace of Canada, was a major contributor to the successful operation of these problem satellites. As demonstrated in 1984 by Space Shuttle Challenger astronaut, Sally Ride, the manipulator arm was used to shake free one of the 21-ft solar arrays of NASA's 2.5 ton Earth Radiation Budget Satellite (ERBS) (ref. 6).

Extra-vehicular activity (EVA) has also rescued several doomed spacecraft, when salvage attempts using the Shuttle manipulator arm were unfruitful. As an instance, in April 1991, U.S. Space Shuttle Atlantis astronauts, Jerome Apt and Jerry Ross, were forced to perform EVA to manually free the stuck high-gain antenna of the \$617 million NASA Gamma Ray Observatory, after orbiter maneuvers utilizing the Shuttle's manipulator arm did not shake it free (ref. 7). To NASA officials and owners of satellites launched from the U.S. Space Shuttle, the STS has definitely proved its utility. Without the benefit of the Shuttle's

EVA and manipulator arm capabilities, the mission success of several NASA launched payloads would have obviously been left in doubt. Many valuable lessons have been learned from these experiences and they will become key tools in the design of future reusable space orbiters, including the ESA's Hermes and Japanese HOPE spaceplanes.

In light of this string of on-orbit difficulties, there is a growing concern throughout the space community as to the source of such problems. But due to the random nature of such aberrations, there is not presently a trend for which one can find a common cause. The best that one can hope to do is concentrate on a particular type of spacecraft failure, in this case, deployment failures.

In accordance with this agenda, the author has chosen to limit the following discussion to appendage failures only. Since it has not been possible while preparing this paper for the author to review the literature fully in this field, the present review cannot claim to be exhaustive. It is intended only to examine probable causes and events surrounding the series of space anomalies, and suggest feasible solutions to preclude such disasters from occurring in the future.

THE PROBLEM WITH DEPLOYABLES

Deployable spacecraft appendage such as antennas, solar arrays and booms perform many functions essential to mission success. Remote satellite operation is achieved through the use of RF communication and telemetry antennas to earth ground stations. In general, they provide the only communication link between Earth and the satellite. Booms are used to deploy scientific experiments, probes, sensors, antennas, etc.. Solar arrays are the primary electrical power source for the majority of spacecraft. They also charge the spacecraft's batteries, so that they can provide the energy necessary for a similar level of payload operation during eclipse periods. The importance of proper solar array deployment cannot be overemphasized in that, failure to deploy an array on-orbit ordinarily results in inability to accomplish mission objectives.

Although appendage devices are extremely critical to spacecraft orbital operation, they suffer from several inherent drawbacks. The most obvious is their increased mechanical complexity. Beginning in the early 1960s, spacecraft designs were initially very conservative. They were low-power, low-weight, mechanically simple and had on-orbit lifetimes of only 6 to 8 months. As launch vehicle maximum payload capabilities increased, so did the size and complexity of satellites. Today, solar array and antenna designers have continued to become more intricate and daring in their designs, despite the problems manufacturers are currently facing in deploying such devices on-orbit. In relation to scientific satellites, and to some extent communication satellites, the trend has been to achieve more objec-

tives with single missions, while attaining longer lifetimes in the harsh space environment, with extreme reliability.

Figure 1 shows an artist's impression of NASA's proposed Space Station Freedom, an ambitious joint venture between the U.S., Japan, Europe and Canada. The \$30 billion station will possess six solar arrays, each spanning 39 ft. W X 112 ft L, and an assortment of booms and antennas. In this scaled-down version of the newly proposed space structure (original configuration utilized 8 solar arrays), the solar arrays are the prime electrical source for the 56 Kilowatt power plant. Critics are concerned that if spacecraft manufacturers are currently having trouble coping with the relatively simple deployment problems they have recently faced, how can they realistically attempt to design and build such a complex structure as the Space Station?

Deployable components are also very fragile devices. They generally cannot support their own weight while in Earth's gravity. To prevent mechanical damage during vehicle launch, they must be kept in a stowed configuration, immobilized by various locking apparatuses (cables, pins, locking mechanisms, etc.). Once in space, these devices are released from their latched position through a series of carefully planned explosive charges (pyrotechnics). Deployment motors are designed to exert low forces on deployment mechanisms; usually only a few pounds. Centrifugal forces and speeds used to aid in the transition from the stowed transfer orbit configuration to full deployment are also kept low. Shock and vibration dampers are used to attenuate the mechanical loads experienced by the spacecraft as appendage reach their "end of travel". The appendage itself must exhibit low contact resistance and electrical noise during electrical transfer, and impose low torques on the spacecraft.

The sequence of appendage deployment is additionally important. During orbital transfer, a spacecraft must rely entirely on its batteries for power. Thus, deployment sequences must be performed within short time schedules. Also, the firing of pyrotechnics to deploy booms, antennas and solar arrays introduce small dynamic loads on the spacecraft. However, these firings must not adversely effect the operation of nearby structures, or interfere with the deployment of other appendage. The basis on which these sequence of events is planned is commonly the result of extensive computer analyses and deployment tests conducted on engineering and qualification models.

Figure 2 shows the ESA's European Remote-Sensing Satellite, ERS-1, deployment sequence during the "Launch and Early-Orbit Phase", or "LEOP". The sequence of deployments is driven primarily by the results of a pyrotechnic shock analysis, which showed that the Synthetic Aperture Radar (SAR) antenna could be deployed with the solar array already out, but the array drive mechanisms had to be locked. The ground deployment testing of the SAR is shown in figure 3. Other important factors include critical timing, satellite space visibility

to one (located in Santiago de Chile) of seven different ground stations, battery-powered deployment, and thermal stability. The four antenna and solar array deployments were activated by pyrotechnics and spring forces (ref. 8).

In addition to the forementioned difficulties, appendage deployment mechanisms are also sensitive to the thermal environment conditions imposed during space operation. Thermal gradients, high and low temperature extremes, and the high vacuum of space can cause mechanical elements to lock or stall, or metal surfaces to weld together. To preclude such catastrophes, exhaustive thermal balance and thermal vacuum testing are done at system level prior to launch, to ensure proper operation once in space.

PROBLEM SOURCES

The 1986 U.S. Space Shuttle Challenger accident left a vivid impression in the minds of many that space operations are not free from catastrophic failures. This incident, along with failures of several expendable launch vehicles which included the European Ariane Rocket, U.S. Atlas/Centaur and Titan rockets compelled launch vehicle manufacturers world-wide to make internal assessments of their own quality, safety and reliability programs.

Following the two year hiatus imposed by the Challenger accident, the number of launch vehicle failures decreased significantly during the latter half of the 1980s. While this trend has continued into the 1990s, a new series of problems have recently emerged — spacecraft failures. The successful launches of the late 80's seemingly gave manufacturers a false sense of confidence concerning the orbital performance of spacecraft. The latest chain of failures has forced a shift in directives for those involved in satellite operations, and the question of space anomalies has now become a major issue.

As previously mentioned, the discussion in this paper is restricted to only those failures resulting from the spacecraft's failure to deploy appendage. Even with such a narrow span of spacecraft failures, the realm of conceivable reasons for satellite deployment problems are far too extensive for discussion here. For the sake of simplification, we shall examine several known factors that can be directly attributed, or highly suspected to be, possible causes of on-orbit spacecraft appendage failures:

- a) mechanical launch loads
- b) on-orbit thermal and solar effects
- c) inadequate ground-based testing
- d) onboard spacecraft pyrotechnics
- e) spacecraft outgassing.

MECHANICAL LAUNCH LOADS

In general, spacecraft are subjected to the most damaging mechanical loads during the launch period. Due to their

delicate nature, satellite appendage is particularly susceptible to dynamic launch loading. However, since very few spacecraft are ever returned to Earth, and satellite repair and rescue missions such as demonstrated by the U.S. Space Shuttle are far and few between, the extent of launch loading damage to these devices is not a factor easily determined. But, past experience has shown that launch conditions have produced profound effects on spacecraft. For example, the first cluster of the U.S. Skylab, launched in 1973, suffered extensive physical damage as a result of the severe vibroacoustic environment experienced by the structure during launch from a two-stage Saturn 5 rocket. The launch vibrations caused the workshop's meteoroid/thermal shield to be torn away, which in turn ripped away one of the pair of solar array wings and caused the other to be jammed in a partially open position by debris. Two astronauts later conducted EVA to free the jammed solar panel (ref. 9).

In terms of causes of some of the current appendage deployment problems, only one is considered suspect to the effects of mechanical loading. The NASA Galileo Jupiter spacecraft is presently speeding towards Earth for a December 1992 gravitational-boost flyby, without the use of its high gain antenna (HGA), stuck in a partially unfurled position. Figure 4 shows a photograph of the flight antenna fully unfurled at JPL, Pasadena, California. Lateral vibrations induced to the HGA structure during the four cross-country truck trips the spacecraft made between California and Florida, have presumably worn away the dry lubricant (molydisulfide) that allows the HGA rib support pins to freely disengage from the central mast during deployment (ref. 10).

It should be noted that the majority of the deployment problems previously outlined in table 1 were discovered during the first few hours on orbit, during the transfer orbit sequence. This has led many to believe that the cause of the events occurred prior to orbital placement. In this respect, the launch environment is deemed a logical problem source. But again, no conclusive data is presently available to confirm this theory.

The high-intensity noise pressure due to engine thrust or aerodynamic forces are the primary sources of spacecraft structural vibration. But, generally speaking, the vibroacoustic launch environments and corresponding design precautions are regarded as being reasonably well understood by the modern engineering community. Each have been heavily documented in literature over the past two decades, many valuable lessons learned have been applied, and a high level of confidence is now believed to exist in this area. Also, aside from the previously mentioned Galileo situation, the present failures in question are not considered to be vibration-induced. Thus, an analysis in terms of vibration and acoustic related effects will be precluded from this discussion.

One dynamics area that is of concern, and where consid-

erable research has been devoted over the past few years is pyrotechnic shock. Pyrotechnic shocks or "pyro" shocks, are very short-duration, high-frequency shocks produced by certain flight events such as engine ignition, explosive separation of booster stages and the release and deployment of satellites and appendage. Typically, primary attention is given to the shock transients experienced by the spacecraft during the vehicle launch stage, whereas on-orbit loads are considered to be of lower-level and less of a threat to the structure.

Charles Moening of the Aerospace Corporation, El Segundo, California, completed a study in 1984 on the cause of failure of eighty-eight (88) U.S. Air Force (USAF) spacecraft and launch vehicles, under USAF Contract No. F04701-C-0084 (ref. 11). One of the most astounding discoveries of Moening's investigation was that 85 of the 88 anomalies (96.5%) were found to be related to pyrotechnic events, or occurred shortly after shock events when the thermal and the vibration environments were relatively benign. The conclusions of Moening's findings, and the results of several meaningful dynamic investigations pursued by the Aerospace Corporation as a whole, have become key parts of MIL-STD-1540 (USAF), "Test Requirements For Space Vehicles", USAF environmental test tailoring and design handbooks, and MIL-A-83577 (USAF), "Test Requirements for Moving Mechanical Assemblies For Space". The overall effect of the suggested design and test guidelines detailed in these documents, and as implemented by suppliers of equipment to the Air Force, are suggested to have at least partially contributed to the launch vehicle success the USAF space program is presently enjoying.

THERMAL AND SOLAR EFFECTS

The Space Environment

Once on orbit, spacecraft must face an array of dissimilar and hostile environments, most of which are foreign to the Earth's atmosphere. Among the varied elements satellites must encounter during their orbital life are high and low temperature extremes, severe electromagnetic (solar) radiation, atomic particle radiation, low vapor pressure (high vacuum), and the absence of gravity. In relation to spacecraft appendage, the large temperature fluctuations that can occur when the satellite moves into the shadow of the Earth during an eclipse are of primary importance.

During an orbital eclipse or as a consequence of the satellite's orientation in space, one side of the satellite, exposed to sunlight, may be at about +150°C whereas the opposite side, in the shadow and facing the blackness of space, may be at -120°C (ref.12). Such large changes of thermal gradients between stationary and rotating components (solar array and antenna drive shafts), have been known to cause unpredictable behavior that includes increased loads, bear-

ing friction and resistance torque on moving surfaces. Also, since deployables extend from the body of the spacecraft they, in general, have low thermal capacities and rely mainly on passive thermal control. Thus, the proper choice of materials and space lubricants are vital keys to appendage on-orbit operation.

Tribology*

The important and critical spacecraft functions provided by deployable appendage involve the relative movement of surfaces in contact. In orbit unlubricated metal surfaces can rapidly weld together or exhibit high friction and wear. Tribology is the science and technology of touching surfaces in relative motion, the main topics being friction, lubrication and wear. A knowledge of tribology is therefore vital to successful spacecraft design and operation. Since 1972, researchers at the European Space Tribology Laboratory (ESTL), England, have done extensive R&D and thermal vacuum testing involving the behavior of spacecraft mechanisms and lubricants. As noted by Dr. Rob Rowntree of ESTL, "tribology has an essential role in the modern spacecraft industry and is, or should be, an integral part of the design process. It is not a process to be added when the design is complete" (ref.13).

It is beyond the scope of this article to assess all the prevalent aspects of tribology, thus for this discussion, only two major areas of tribology shall be considered: space mechanisms and lubricants.

Spacecraft mechanisms are generally made to be non-reversible. This is due to the fact that satellites are primarily not designed to be recoverable, thus their appendage is intended to remain in a locked position for the duration of their orbital life. Early spacecraft had few moving parts and very short lives. Mechanisms were relatively simple and conventional terrestrial vacuum lubricants were initially adequate. Today, the mechanical complexity of satellites have increased dramatically. Since redundancy of large satellite appendage such as solar arrays is not possible, parallel or serial duplication of their associated drive and deployment mechanisms is employed to provide a higher level of reliability. Sound tribological practices and testing conducted prior to spacecraft design completion have contributed significantly to the improved operation of spacecraft mechanisms in the low temperature, thermal vacuum of space.

The reliable rotation of solar arrays, gimbals, scanning mechanisms and momentum wheels in the extreme coldness of space is highly dependent upon the lubricant used on bearing or mating mechanical interfaces. The two major classes of space lubricants are dry/solid film and liquid/fluid lubricants. The primary space solid lubricants presently used in industry are MoS₂, PTFE and Pb (Lead). Major types of liquid lubricants include refined mineral oils, synthetic oils (silicones), esters and perfluorinated

polyethers.

Table 2 outlines the pros and cons of dry/solid and liquid/fluid lubricants. As noted, only solid lubrication is practical for spacecraft mechanisms used at cryogenic temperatures. Another substantial advantage dry lubricating films is that when applied to bearings, the resulting torques are independent of temperature and rotational speed. Also, for certain types of cleanliness requirements, dry lubricants are preferred. However, dry lubricants perform poorly in air, and care in handling must therefore be exercised during the ground test phase where, in addition, much greater loads than in orbit can be encountered. Some of the pros of liquid lubricants are they that allow good radial thermal conductance, produce low torque noise in rotating bearings, and can be used in air. On the down side, the viscosity of fluids varies considerably with temperature which is unacceptable in some applications. Also, liquid lubricants have a small operational temperature range.

***Note:** Section based on tribology research, testing and published literature issued by the European Space Tribology Laboratory, UK.

LIMITATIONS OF LABORATORY TESTING

Ground-based testing accounts for roughly 25-30% of the total cost of a spacecraft, with the average price of a modern communications satellite being in excess of \$60 million. Thus, the cost-effectiveness of exhaustive environmental testing such as vehicle level vibration, acoustic and thermal vacuum testing is easily demonstrated in relation to the satellite's high price tag, and possible financial repercussions of an on-orbit insurance loss.

The key to the effectiveness of any laboratory test is that it be representative of the intended operating environment of the test article. The size and complexity of satellite appendage often requires unique simulation techniques to achieve this objective. While the quality and confidence in space simulation test methods have progressed dramatically since the early 1960s, limitations still remain.

Vibration Testing

Vehicle-level vibration testing is suggested to provide the most accurate simulation of launch conditions. Due to the increasing size and weight of today's satellites (3-5 tons), multi-shaker vibration test systems have become the norm. But, true launch vibrations occur simultaneously in multiple spacecraft axes, thus requiring the use of a multi-axis vibration test facility for comparable laboratory reproduction.

Until recently, spacecraft manufacturers have been without the capability to excite an entire space satellite concurrently in all three orthogonal directions. Figure 6 shows a photo of the Japanese National Aeronautics and Space

Development Agency's (NASDA) Vibration Test Facility at the Tsukuba Space Center, Japan. The system, which became operational during the summer of 1991, is capable of testing satellites weighing up to 4.5 tons in all three axes (X,Y,Z), without having to reposition the test article. The NASDA installation, designed by the team of Ling Dynamic Systems, UK and Akashi Seisakusho, Japan, employs ten (10) - 48,000 lbf electrodynamic shakers coupled to a cubic vibration table offering a test area of 9 m² (96 ft²). Presently, it is the largest multi-shaker system in the world (ref.14).

The European Space and Research Technology Centre (ESTEC), the Netherlands, the environmental testing arm of the ESA, is currently pursuing many of the same unique benefits demonstrated by the NASDA system in their proposed Hydraulic-Shaker Test Facility for testing the large Ariane payloads, such as the Hermes Spaceplane. Once complete, the ESTEC vibration system will utilize several long-stroke, high force hydraulic exciters to simulate spacecraft launch conditions.

Another shortcoming of vibration testing is one that does not involve the application of vibration, but instead the decision of whether to apply electrical power to the satellite during test. Moening's forementioned study on Air Force spacecraft notes that powering-up satellites systems during vibration testing, while complicating the tests, has made it possible to detect 'mission-catastrophic' anomalies such as electrical shorts which would have occurred in the high acoustic and vibration environment of a launch (under normal circumstances, power is not applied to satellite appendage or electrical systems during launch). The objective of continuous monitoring of perceptive parameters is to detect intermittent failures that may appear normal during the initial on-orbit checkout. Thus, it is to be used as a diagnostic tool to reveal failures that would otherwise occur and go undetected during launch, only to surface later while the spacecraft is on orbit.

This change in directives is further spelled out in MIL-STD-1540B, of which personnel at the Aerospace Corporation were key contributors. As stated in the specification, for space vehicle qualification testing: "during the test, electrical and electronic components, even if not operating during launch, shall be electrically energized and sequenced through operational modes." However, the document also advises the non-application of power to those components or systems that might suffer damage during testing, due to energization.

Pyroshock Testing

Pyrotechnic shock testing deficiencies have been outlined by several practitioners, including Moening (ref. 11), Chalmers (ref.15), Czjakowski and Rehard (ref.16). Moening's USAF spacecraft study revealed that inadequacies existed in the use of pyroshock for component, piece

part, qualification, and system level testing and screening. Chalmers conducted a review of pyroshock test techniques in 1990, which showed major limitations in terms of instrumentation measurement capabilities and methods presently being undertaken to increase the confidence of testing. Czajkowski and Rehard also observed several instrumentation problems which involved use of anti-aliasing filters and analog/digital analyzers. It was suggested that very high-frequency sampling rates preclude the use of the filters. The underlying consequence of these testing methodology and equipment limitations is that a possible undertest of the test article results, which does not adequately prepare the spacecraft for the shock levels experienced during launch.

In addition, engineers have also cited that certain pyroshock test specifications were too stringent, and not practical. As an example, the +3 dB tolerance stipulated in USAF MIL-STD-1540A was widened to +6 dB in Rev. B, because the previous specification was not realistic, extremely difficult for contractors to adhere to, and was not compatible with industry equipment and test repeatability.

Deployment Testing

Various methods are used for deployment testing which include neutral-buoyancy testing, air-bearing support systems, and "zero-g" gravity compensation fixtures. There are drawbacks to each technique. Neutral-buoyancy tests have shown to be well-suited for astronaut extra-vehicular activity (EVA) training and space suit testing, but generally are not practical or feasible for most conventional space programs. They require large water reserves and are expensive to maintain. Air-bearing support systems (see figure 6) offer relative ease of operation and much lower system costs as compared to neutral-buoyancy cells. However, such setups are often large, bulky and complex. In addition, such intricate fixturing has been suspected of introducing added resistance loads to the device under test.

It has been concluded by the engineering community that it is virtually impossible to simulate the zero gravity ("zero-g") environment of outer-space in a laboratory test. As long as the test system is within the bounds of the Earth's atmosphere, there will always be some level of gravitational forces acting upon it. Thus, the objective of "zero-g" deployment testing is not so much to provide a true replication of the weightlessness of space, but to suspend the deployable device in a very low-gravity state by which forces acting upon it are considered negligible (this is generally achieved using 1-g off-loading, typically in the deployment mechanisms vertical plane). Although the test may not be representative of the environment (due to air drag, etc.), it does allow spacecraft designers to verify friction margins and appendage functionality.

The use of "zero-g" test rigs and fixtures have proven to be very efficient provided the test set-up is simple and there

is no variation of the potential energy of the item under test (i.e. center of gravity of the test item moves in the vertical plane). Figure 7 shows the "zero-g" test rig used for deployment testing of the ESA's OLYMPUS satellite, at the David Florida Laboratory in Ottawa, Canada. The test rig, designed and built by Spar Aerospace, Toronto, Canada, utilizes a series of constant load springs which were carefully balanced to allow the satellite's solar wings to take their on-orbit "zero-g" shape with little error (ref.17).

"Zero-g" test under ambient condition have been very fruitful, but there is doubt on the value of such test conducted under thermal vacuum conditions. The most important concern is the influence of the test rig on the test data. Since both the deployable and test rig will see virtually the same thermal conditions inside the chamber, the thermal influences of the test rig must be accounted for in order for the test to be considered valid. Also, when deployment tests are done in a thermal vacuum chamber, a certain thermal environment is generally chosen (usually, a cold or hot soak) which will deviate significantly from the real circumstances. Thus, it is often very difficult to create representative temperature gradients.

Thermal Vacuum Testing

Rigorous thermal vacuum (T/V) testing has proved to be of great value in assessing the reliability of mechanisms under conditions which simulate the space environment. The major limitation of T/V testing has been the internal space capacities of modern chambers. Figure 8 shows the Galileo Jupiter spacecraft undergoing T/V testing in the Space Simulator Chamber at JPL. The 25-ft Space Simulator, built in 1961, has a test volume of 20-ft D X 25-ft H. Throughout its many years of operation, the facility has been sufficient for most spacecraft designs. However, the increasingly wide span of modern solar arrays and size of large deployable structures such as Synthetic Aperture Radar (SAR) antennas makes practical testing of these devices in a T/V chamber, even the size of the JPL installation, unfeasible. Partial solar array deployments are generally performed under vacuum conditions, with RF antennas being the only assemblies able to be fully deployed.

T/V chambers capable of handling extremely lengthy deployables are still a long ways from practical development. However, progress has been made by various testing organizations in an effort to overcome this deficiency. For example, in 1987, the ESTEC made operational the Large Space Simulator (LSS). The LSS, shown in figure 9, is the largest facility of its kind in Europe, with internal chamber dimensions of 33-ft D X 50-ft H. Uniquely different from most T/V chambers presently in existence, the LSS utilizes an advanced motion simulator to provide realistic solar and thermal profiles, and to simulate the relative spinning motion of satellites in space. Due to the volume of the LSS,

the ESA Hipparcos satellite was able to be T/V tested in 1989, with its solar panels and telescope baffles fully deployed under simulated space conditions (see figure 10).

SPACECRAFT PYROTECHNICS*

For single-function mechanical operations, the efficiency, reliability and speed of pyrotechnic actuators ("pyros") are without parallel. The role of pyros is to aid in the release of long booms, large antenna dishes and solar arrays; open/close valves; push/pull loads; and sever wires and bolts used as launch restraints, etc. However, onboard explosive firings have themselves been seen as a source of appendage problems. Self-induced shocks occur principally when pyrotechnic and pneumatic devices are actuated to initiate the forementioned events. But, spacecraft dynamic analysis utilizing computer models and results of ground testing, have shown that these acceleration levels are much lower those induced during launch, and exhibit little damage potential to the structure. Additionally, shock and vibration dampers are commonly employed to limit the effects of pyrotechnic discharges.

The reliability of spacecraft pyrotechnics has also been suspect to some observers. The fundamental requirement of a pyrotechnic device is that it detonate reliably when commanded and not under any other circumstance (inadvertent firing). Although very few cases of non-firing of pyrotechnics on-orbit have ever been reported, the predominate question generally asked by ground controllers during the early moments of any deployment problem is, "Did the pyros fire correctly?". This is because many times the only indication controllers have as to whether a pyrotechnic explosive actually detonated as commanded, comes from the mechanical linkage of the appendage in question. Electrical signals fed back from the closing of micro-switches as the deployable moves into its operational position, signifies pyrotechnic release as well as appendage deployment. However, other, more indicative methods of verifying pyro firings, are presently being pursued by several spacecraft manufacturers.

Unlike all other hardware onboard a spacecraft, explosive-based components are only usable once. That is to say, the pyrotechnic to be used for flight can never be fully tested before it is required to operate in space. Confidence can only be generated by the performance of like items fired for that purpose. Generally, a large number of samples must be fired in the test program to build any significant level of confidence. The test program must be comprehensive and complete; merely firing a few items under given conditions will not suffice. Also, the number of test items must be large enough to allow firings under all the various chosen conditions. But, even after such extensive testing, there is still no guarantee that the actual units used in the spacecraft will function correctly in orbit. Thus, for reasons of safety and reliability, pyrotechnics are also duplicated in series or

in parallel, according to defined requirements of failure tolerance.

***Note:** Section based on reference 18

SPACECRAFT OUTGASSING

Spacecraft outgassing, or "ballooning" as is sometimes referred, is a phenomenon that occurs as a spacecraft transitions from one atmospheric pressure level to another. The most common form of outgassing generally happens during vehicle launch. Under the normal air pressure conditions of Earth, components such as insulation thermal blankets fit loosely over the body of the spacecraft, and are sealed. The only openings in the blanket are located around rotating shafts, etc. It is known that large areas of material with high outgassing rates are only pumped through such small orifices in space. During ascent into space, the air pressure surrounding the satellite decreases, causing a pressure imbalance between the interior and exterior of the spacecraft. This forces the air trapped beneath the blanket to be pushed outward, thus the ballooning effect is created. While it is understood that some outgassing will always occur, obviously the looser the fit of the thermal blanket to the spacecraft, the more pronounced will be the ballooning. The importance of this scenario is that the blanket will generally stay in this inflated state as long as it remains in space. The danger to appendage is that when instructed to deploy, there is a much greater chance of it snagging on a piece of the blanket, possibly creating an incurable deployment problem.

Another problem with outgassing is that the condition is very difficult to detect during ground testing. Because of the high pumping rates required (the pumping speed of space is essentially infinite), the event is extremely difficult to simulate with a thermal vacuum chamber. The problem becomes more of a challenge as the size of the chamber increases, which is necessary for vehicle-level testing.

A great deal more research needs to be done in this area (Scialdone (ref. 19) and other researchers have done significant studies in this area), which has potentially catastrophic effects on future satellites. Keeping in mind that the outgassing rate varies with each spacecraft, and is influenced by the size and complexity of the design.

LESSONS LEARNED FROM ANIK-E2

On April 12, 1991 Telesat Canada developed difficulties with the K-band and C-band antennas of its Anik E2 satellite not being able to deploy either after the initial command sequence was sent to the satellite. An anomaly team comprised of engineers from the spacecraft design team, Spar Aerospace Ltd., Canada and GE Astro Space, New Jersey, was quickly formed. The K-band antenna unexpectedly freed itself on April 19, while the C-band antenna

remained stuck. The GE/Spar team later utilized a series of thermal and dynamic maneuvers to finally free the antenna on July 3, 1991. The extensive series of measures, which included a 'dual spin turn' reversal of the satellite, were previously unprecedented for a recovery attempt of a commercial satellite (ref.19).

Although the satellite was nearly claimed as an \$208 million (\$240 million Canadian dollars) insurance write-off, several valuable lessons were learned from the Anik experience.

1. Technical ingenuity is the key. The successful deployment of the Anik's C-band antenna was the result of the quick response, timely decisions and carefully planned recovery maneuvers issued by the 12-man team of Spar Aerospace and GE Astro Space engineers. The GE/Spar team, whose activities were coordinated by Doug Jung of Spar, made several critical decisions during the early moments of the Anik experience, including the recommendation to Telesat Canada officials not to deploy the satellite's solar arrays. The extension of the spacecraft's solar panels would have prevented any viable use of dynamic spin maneuvers to free the stuck antenna. In addition, meticulous calculations were also performed by the team used to estimate the rate of spin necessary to overcome the resistance of the presumed thermal blanket holding the appendage, without damaging the antenna during the deployment attempt.

What can be learned by other spacecraft manufacturers is that their most valuable asset is indeed their employees. The best resources available to help remedy an appendage problem usually comes from within the organization(s) responsible for the design and test of the spacecraft. Thus, in general, the same technical staff that is responsible for the satellite's construction, should be utilized in the recovery effort.

2. Satellite maneuvers are effective salvage tools. The Anik E2 recovery experience was not the first instance of dynamic and thermal maneuvers being used to free appendage. However, the exercise was unprecedented for the use of exhaustive procedures. The immediate lesson learned is that, although the satellite may be sufficiently insured for a loss, the owner should pursue every conceivable exercise (within the design limitations of the spacecraft and with concurrence of insurance underwriters) to achieve recovery. Secondly, since such maneuvers have been met with success, they should continue to be used to the extent possible.

3. Innovative spacecraft designs are necessary. The Satcom 5000 satellite platform, designed and manufactured by GE Astro Space, was clearly a well thought-out design that contributed greatly to the success of the Anik. Had the

solar arrays not been designed to be operational in a stowed position, the owners would have been forced to deploy the solar panels before the batteries were depleted. As a consequence, maneuvers to free the stuck antennas would have been virtually impossible to accomplish with the solar arrays extended.

As previously mentioned, spacecraft appendage designs are generally non-reversible and very unforgiving. As an example, the NASA Galileo spacecraft design does not allow for the remote deployment reversal of its high gain antenna. Had such a capability been employed in its design, the present status of the antenna might have easily been corrected. In light of such instances, spacecraft designers should make detailed evaluations of present and future designs, and employ creative techniques to allow potential appendage problems in space to be recoverable.

4. Satellite spares and ground simulation are of vital importance. Remote failure analysis of a satellite is a task often difficult to visualize without some frame of reference. This is mainly due to the fact that telemetry data read back from the satellite is often non-conclusive. The Anik-E1, which was to be launched several months following the Anik-E2, was effectively used to pinpoint the cause of the Anik-E2 failure. Also, numerous environmental tests utilizing the Anik-E1 were conducted at the David Florida Laboratory, Ottawa, Canada. These tests ascertained the antenna could be deployed under various failure scenarios; quantified the forces required and the forces it could withstand; and verified any improvements that would be made on Anik-E1.

It should be noted that engineers at JPL are currently utilizing the flight spare of the Galileo spacecraft antenna to create an accurate picture of the antenna deployment situation. The spare is also being used to plan the course of feasible deployment events during the spacecraft's second Earth flyby in December 1992 (ref. 10).

Thus, the importance of functional flight spares available on the ground cannot be over emphasized. The ability to identify the source of an deployment problem, and undertake recovery maneuvers in the laboratory without consequence to the in-orbit spacecraft, make them invaluable tools.

WHAT CAN BE DONE?

Spacecraft failures are perceived as technical risks of being in the satellite business. But, there are still steps that can be taken by owners and manufacturers to help reduce these risks.

1. Continuation of spacecraft technical meetings, symposiums and workshops. Space symposiums and conferences such as the one today are definitely an outgrowth of the tough times experienced in the 1980s, and are a vital

part of a plan for industry as a whole to learn and grow together. Spacecraft safety and reliability should continue to be the main focus, with increased participation by other related technical societies. In particular, those organizations specializing in areas such as space tribology and structural mechanics.

2. Public disclosures should be made by manufacturers that have experienced failures, to help preclude future anomalies. The consensus is, when it comes to matters of this nature, it is in the interest of all industry to have an open discourse concerning spacecraft failures. Despite the competitiveness of the space market and the nature of the business, there are no true winners or losers when one speaks in terms of a loss of a satellite. In the end, worldwide insurance premiums will increase, making it difficult for all manufacturers to obtain spacecraft insurance, and the overall confidence level in space travel will be again left in doubt.

3. Increased test effectiveness. Testing builds a higher level of confidence, validates designs, and increases spacecraft reliability. System and vehicle level testing have shown the most promise in evaluating the performance of appendage. As noted by Trafton (ref.4), many of the recent deployment failures could have been uncovered only by testing at the vehicle level, i.e., after the deployable was fitted to the spacecraft.

Although there is certainly a level of testing that a spacecraft manufacturer cannot go to because it is too cost prohibitive, efforts should also be taken to provide a closer simulation of the launch and space environments. Test stages should follow closely the sequence of events that the spacecraft experiences from launch to the end of its orbital life. For example, vibration, acoustic and pyroshock testing should be performed in the manner they will most likely occur during launch. In general, a satellite is subjected to a combination of dynamic environments. However, to simplify testing, they are usually simulated separately.

4. Plan for failure. There is generally a very narrow "window of opportunity" during the early stages of an event such as a solar array deployment anomaly (typically less than 24 hours), before spacecraft batteries are depleted. This does not give manufacturers much time to assemble an anomaly team or come up with an effective plan of recovery, if salvage attempts are to be successful. Thus, many of the owners of spacecraft that have experienced appendage-related problems have been caught totally off-guard.

In the future, it is foreseen that spacecraft anomaly teams will become as common an occurrence as design teams. They will be formed prior to vehicle launch, and possibly wait in a "standby" mode until needed. Once called into action, the probability of their success will rely heavily on

such factors as real-time data analysis, thermal and dynamic maneuvers (if necessary), and knowing the safety/design limits of the spacecraft.

FINAL REMARKS

The intent of this article was to raise the general level of awareness concerning on-orbit appendage deployment problems. It was the author's hope to spark sufficient interest in the area such that spacecraft manufacturers would realize the seriousness of these aberrations, and the possible repercussions of dismissing them as mere random occurrences. Also, it is hoped that the lessons learned from these situations will help preclude future appendage problems, or at least provide owners and manufacturers with a better idea of how to deal with them.

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TABLE 1

**SUMMARY OF SIGNIFICANT SPACECRAFT
APPENDAGE DEPLOYMENT ANOMALIES**

SPACECRAFT/ YEAR LAUNCHED	PROBLEM	CAUSE
APPLE (1981) #	Jammed Solar Array	Solar Array Latch Stuck
INSAT 1A (1982)#	Solar Sail Failed To Deploy	Inoperative Mechanical Latch
INSAT 1B (1983)*	Unable To Position Solar Array	Thermal Binding Of Deployment Mechanism
ARABSAT 1A (1985)*	Failure To Deploy Solar Array, C-band Antenna	Mechanical Interference
TVSAT 1 (1987)^	Failure To Deploy Solar Array	Deployment Latching Mechanism Failed to Unlock
OLYMPUS 1 (1989)*	Total Power Loss In One Solar Array	Electrical Short In Cable Harness
GALILEO (1989)#	High Gain Antenna Failed To Deploy	Cold Welding In Ball And Socket Joint
MAGELLAN (1990)#	Solar Array Failed To Latch	Microswitch Misadjusted
ANIK-E2 (1991)*	K and C-band Antenna Deployment Problems	Thermal Blanket Interference
JERS-1 (1992)*	Radar Antenna Failed To Deploy	Wrong Software Command Sequence

Note: Based on failure summary generated by T.W. Trafton of the Aerospace Company, 1991.

* Problem resolved or full recovery of spacecraft achieved

Spacecraft usable without functioning of deployable

^ Spacecraft claimed as loss

TABLE 2

RELATIVE MERITS OF SOLID & LIQUID SPACE LUBRICANTS

DRY LUBRICANTS	WET LUBRICANTS
NEGLECTIBLE VAPOUR PRESSURE	FINITE VAPOUR PRESSURE
WIDE OPERATING TEMPERATURE	VISCOSITY, CREEP & VP ALL TEMPERATURE DEPENDENT
NEGLECTIBLE SURFACE MIGRATION (DEBRIS CAN FLOAT FREE)	SEALS REQUIRED
VALID ACCELERATED TESTING	INVALID ACCELERATED TESTING
SHORT LIFE IN LABORATORY AIR	INSENSITIVE TO AIR OR VACUUM
DEBRIS CAUSES FRICTIONAL NOISE	LOW FRICTIONAL NOISE
FRICTION SPEED INDEPENDENT	FRICTION SPEED DEPENDENT
LIFE DETERMINED BY LUBRICANT WEAR	LIFE DETERMINED BY LUBRICANT DEGRADATION
POOR THERMAL CHARACTERISTICS	'HIGH' THERMAL CONDUCTANCE
ELECTRICALLY CONDUCTIVE	ELECTRICALLY INSULATING

NOTE: COURTESY OF THE EUROPEAN SPACE TRIBOLOGY LABORATORY.



FIGURE 1. ARTIST'S CONCEPTION OF SPACE STATION FREEDOM. (ARTIST-TOM BUZBEE)

Nominal operations sequence for the Launch and Early-Orbit Phase (LEOP)

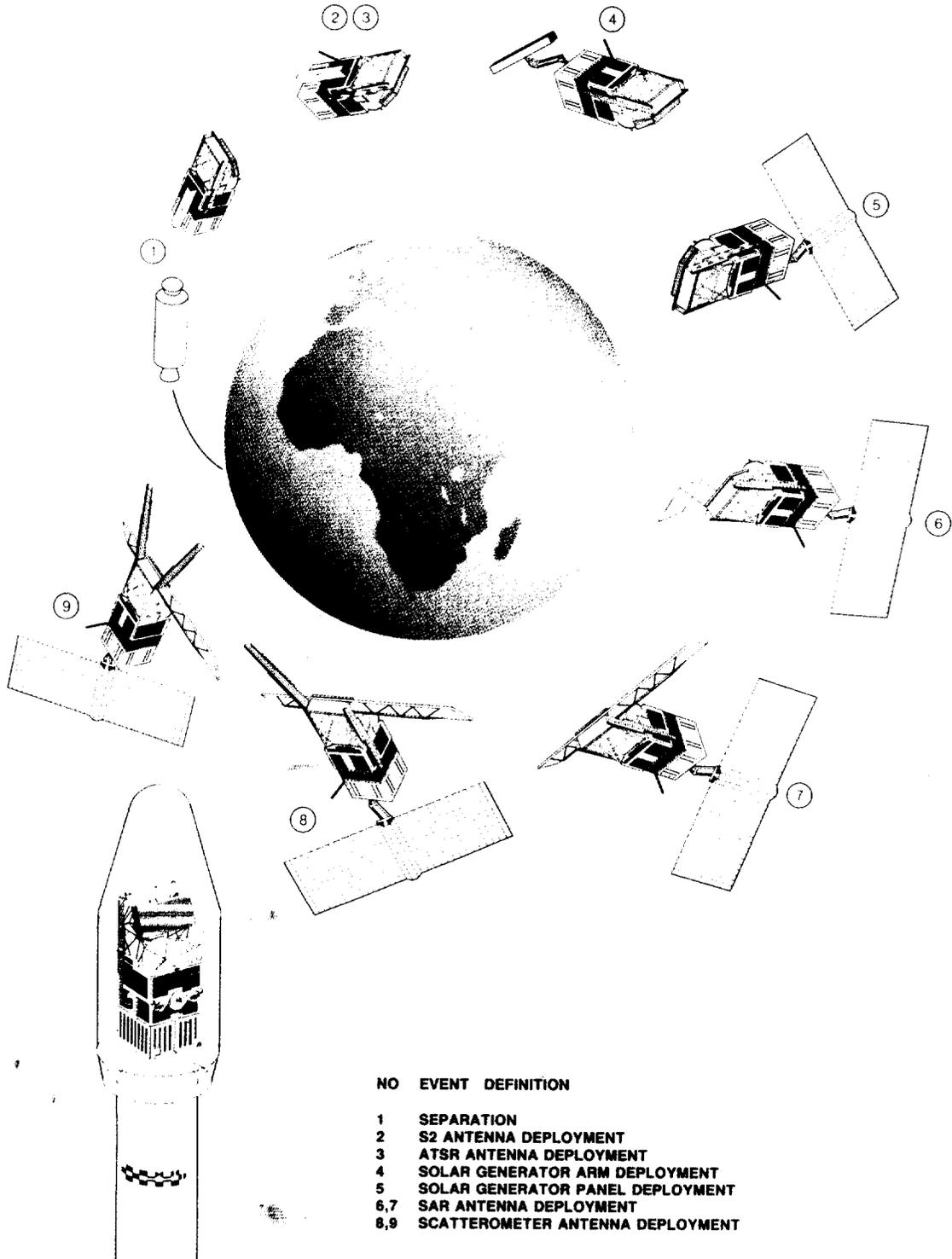


FIGURE 2. THE EUROPEAN REMOTE-SENSING SATELLITE, ERS-1, ON-ORBIT DEPLOYMENT SEQUENCE. (COURTESY OF THE EUROPEAN SPACE AGENCY AND ESA BULLETIN)

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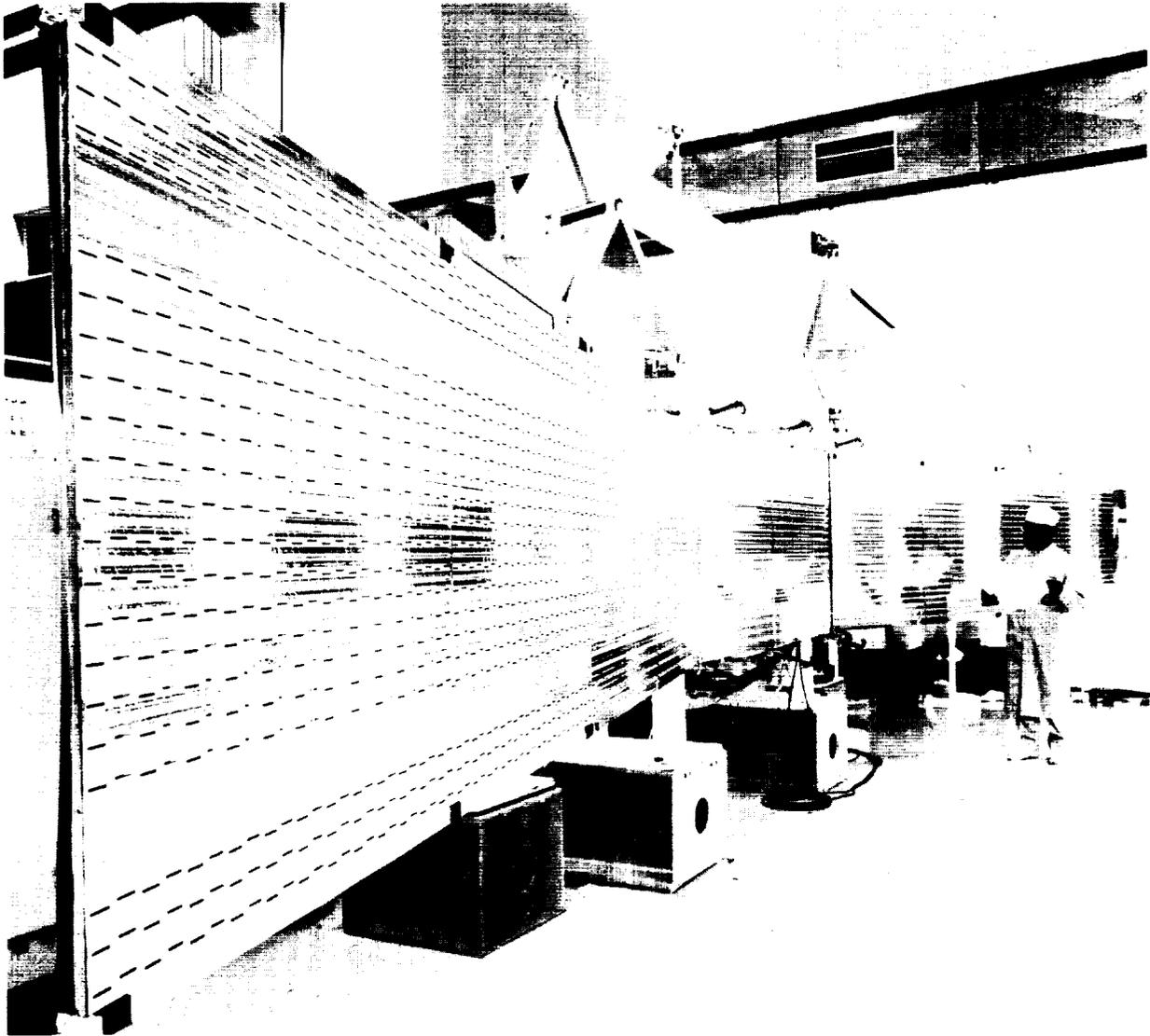


FIGURE 3. SYNTHETIC APERTURE RADAR (SAR) ANTENNA OF ERS-1 UNDERGOING GROUND DEPLOYMENT TESTING. (COURTESY OF THE EUROPEAN SPACE AGENCY AND ESA BULLETIN)

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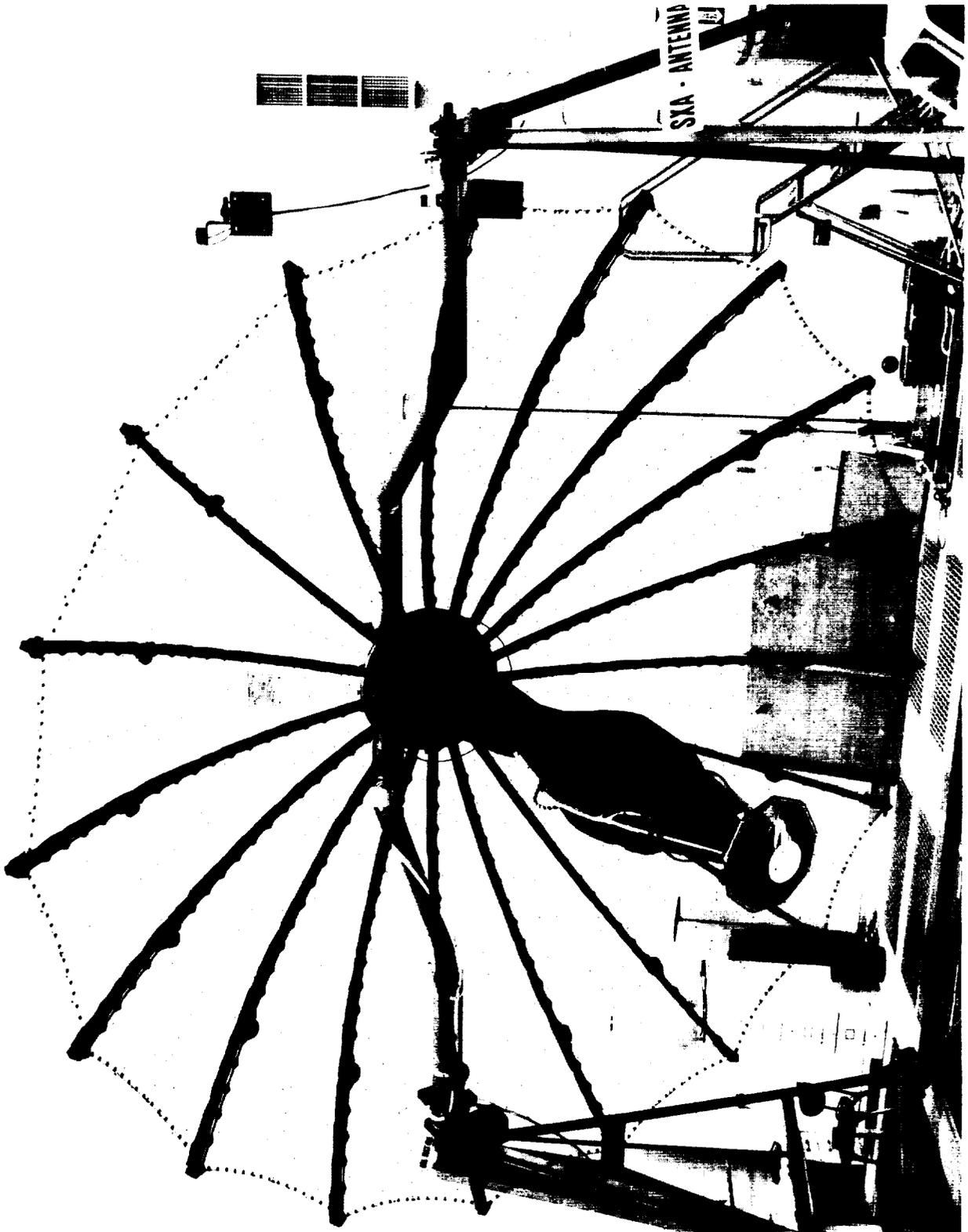


FIGURE 4. FULL DEPLOYMENT OF GALILEO FLIGHT MODEL, HIGH GAIN ANTENNA (HGA) AT JPL. (COURTESY OF THE JET PROPULSION LABORATORY)

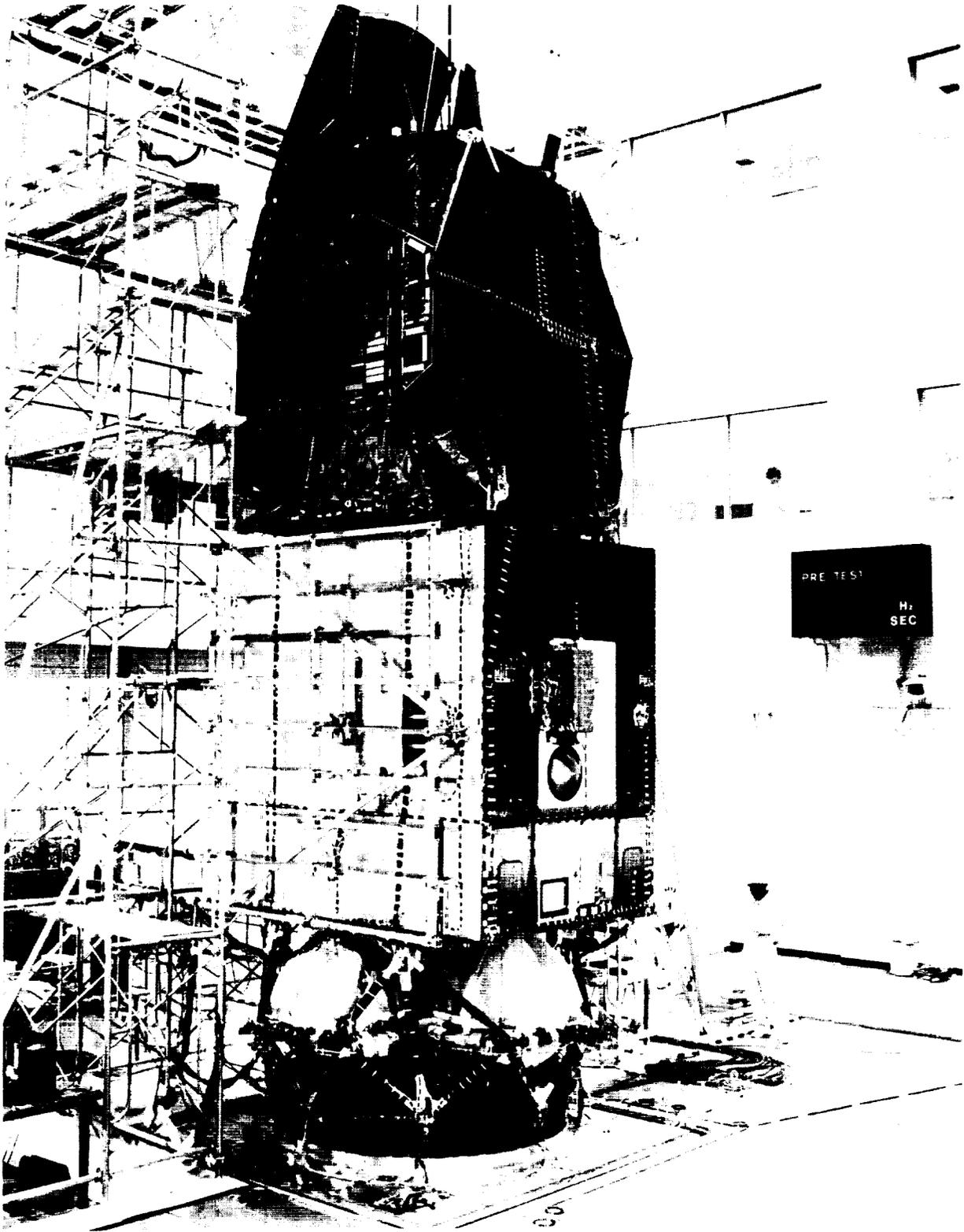


FIGURE 5. ENGINEERING TEST SATELLITE, ETS-1, UNDERGOING VIBRATION TESTING AT NASDA'S TSUKUBA SPACE CENTER, JAPAN. THE VIBRATION SYSTEM IS PRESENTLY THE LARGEST MULTI-SHAKER TEST FACILITY IN THE WORLD. (COURTESY OF THE NATIONAL SPACE DEVELOPMENT AGENCY, JAPAN)

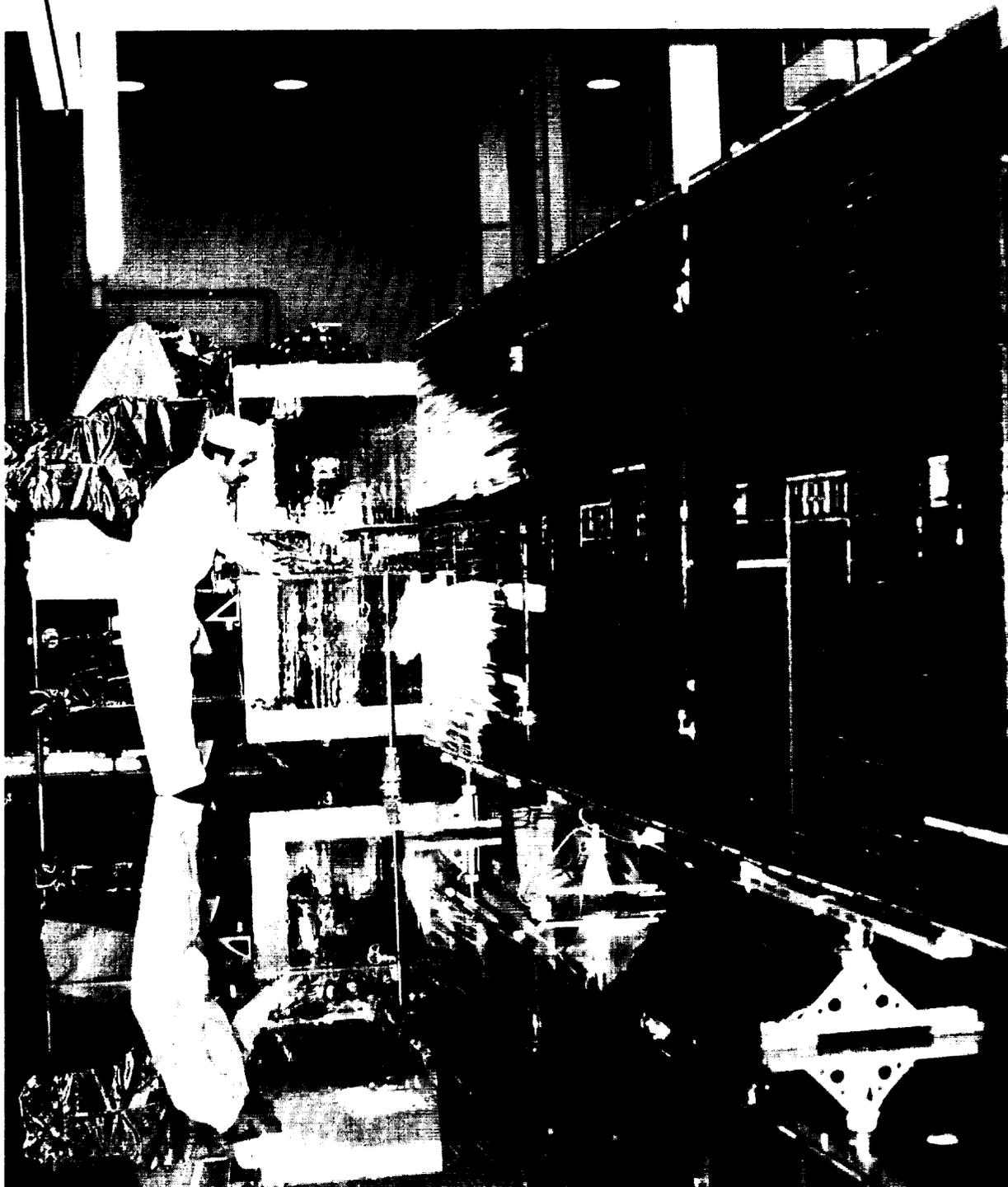


FIGURE 6. SOLAR ARRAY DEPLOYMENT TESTING USING AN AIR-BEARING SUPPORT SYSTEM AT GE ASTRO SPACE, NJ. (COURTESY OF GE ASTRO SPACE)

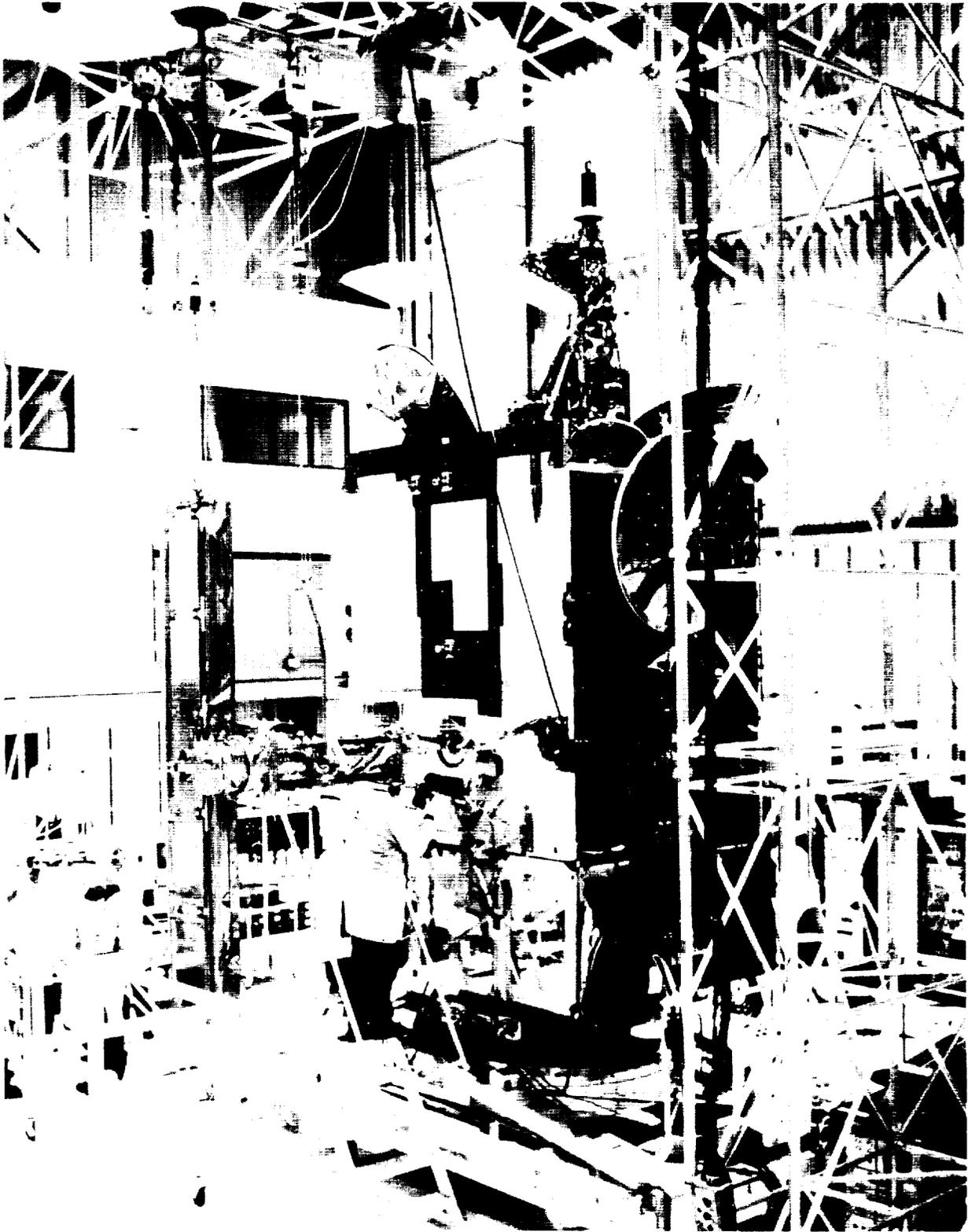


FIGURE 7. SPECIAL "ZERO-GRAVITY" DEPLOYMENT TEST RIG USED TO TEST OLYMPUS SATELLITE AT THE DAVID FLORIDA LABORATORY, CANADA. (COURTESY OF CANADIAN CROWN)

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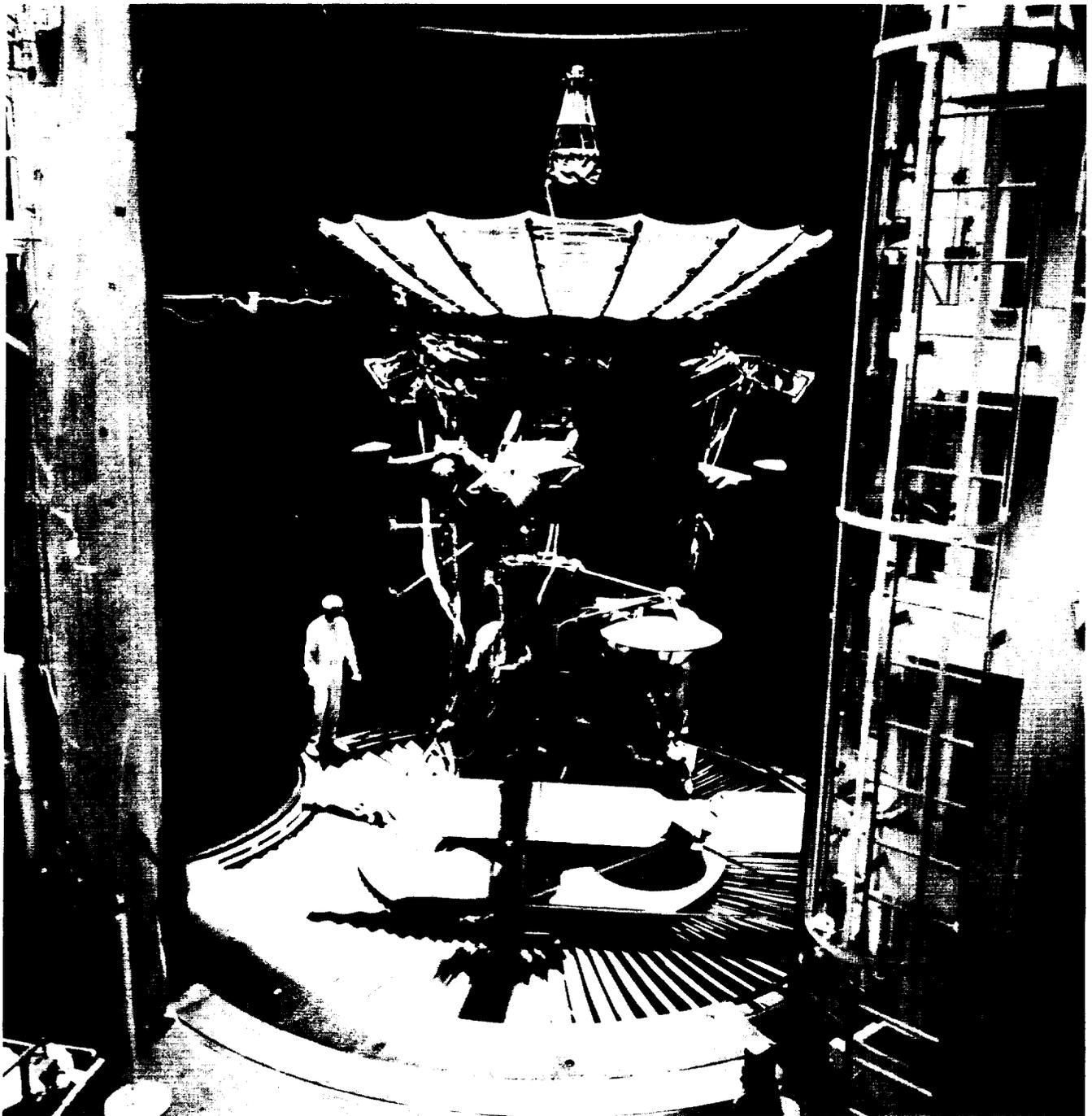


FIGURE 8. NASA GALILEO SPACECRAFT IN 25-FT SPACE SIMULATOR CHAMBER AT JPL. (COURTESY OF THE JET PROPULSION LABORATORY)

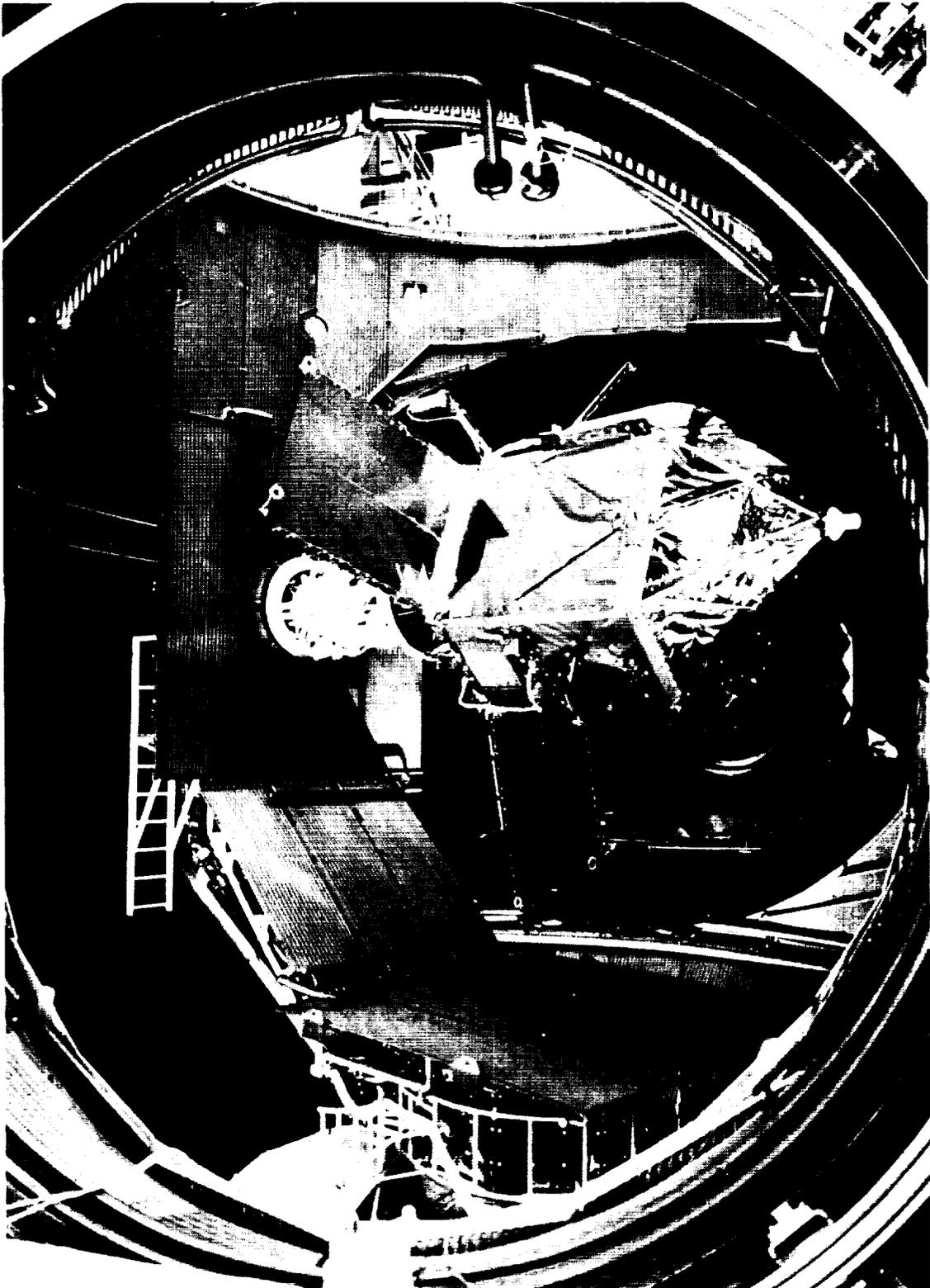


FIGURE 9. EUROPEAN SPACE AGENCY'S (ESA) HIPPARCOS SATELLITE UNDERGOING THERMAL VACUUM TESTING IN THE LARGE SPACE SIMULATOR (LSS) FACILITY AT ESTEC, THE NETHERLANDS. (COURTESY OF THE EUROPEAN SPACE AGENCY AND ESA BULLETIN)

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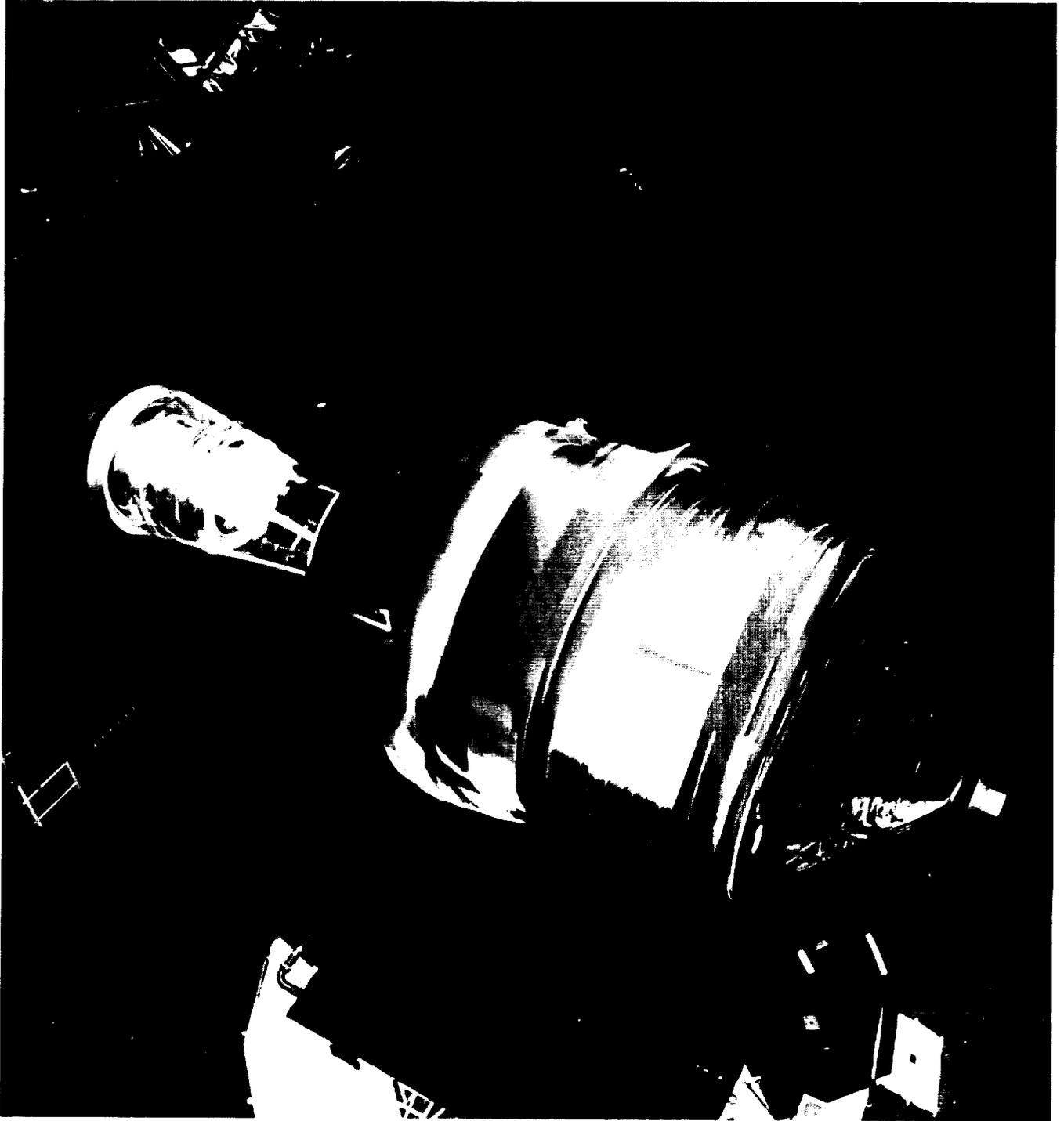


FIGURE 10. ESA'S HIPPARCOS SATELLITE BEING ROTATED ABOUT ITS SPIN AXIS WITH SOLAR PANELS FULLY DEPLOYED, AT THE LARGE SPACE SIMULATOR (LSS) FACILITY AT ESTEC, THE NETHERLANDS. (COURTESY OF THE EUROPEAN SPACE AGENCY AND ESA BULLETIN)

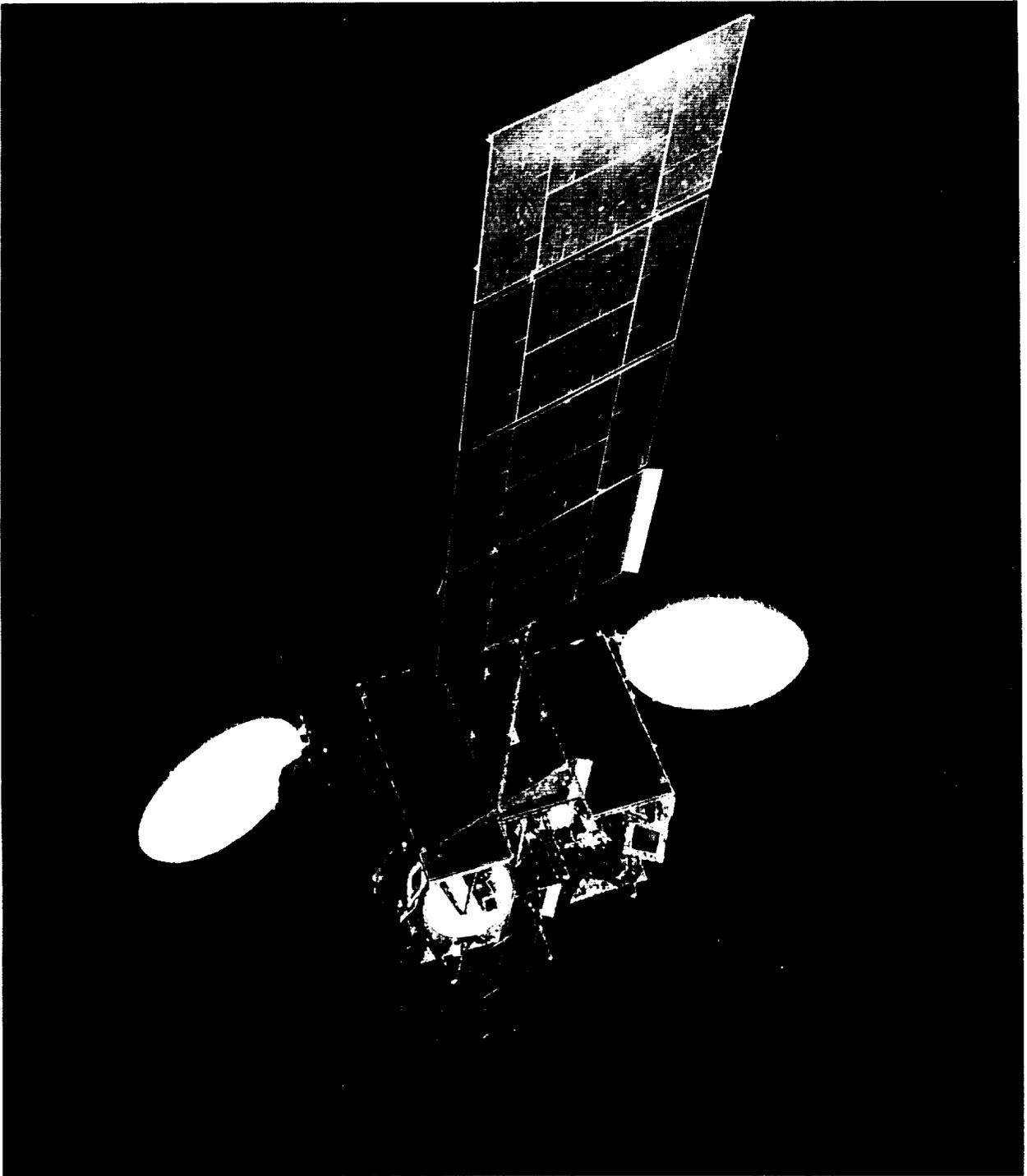


FIGURE 11. TELESAT CANADA'S ANIK-E2 SATELLITE. (COURTESY OF SPAR AEROSPACE, LTD.)